Model-based Development of Energy-efficient Automation Systems

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Abstract

The paper presents an ongoing work towards a methodology for the model-based engineering of energy-efficient automation systems. Energy consumption is an increasingly important decision criterion, which has to be included in the search for good architectural and design alternatives.

As a result of the work, models of automation systems are developed that allow the proper specification of energy consumption. This property can then be evaluated as part of a more general evaluation function. Such a performance analysis requires a model with a well-defined semantics that can be evaluated by simulation or numerical analysis or even used for an automatic optimization of this non-functional property.

We propose to use the UML [10] profile for the Modeling and Analysis of Real-Time and Embedded systems (MARTE) [9], which can be applied for achieving this aim. The second task is to transform these models into a Petri net, which allows a direct performance evaluation.

A small lab setup is realized based on the energy-controllable ATMEL microcontroller ATxmega128A1 and evaluation board. The function of the device and its operating modes are presented as UML models. They are transformed into Petri Nets that allow the developer to estimate the energy consumption and to find the best possible control algorithm in terms of energy consumption minimum.

1. Introduction

Complex technical processes and automation systems which control these processes play a more and more important role. Nowadays, complex systems themselves can be efficiently controlled by means of the available control units. This is based on system design methods which can check the operation modes with the help of a model already before the realization of an "embedded system". In this case, the correct adoption of the desired functions into the classical design process is in the foreground.

In addition, such properties like timeliness and reliability are decisive in the embedded systems by means of which automation systems are controlled or realized. Another non-functional property which is of great importance in the current discussion about resource-efficient management is the energy consumption of these systems [11]. While some components in the industry like, e.g., microcontrollers are developed already with low power consumption, we point out that an energy-efficient automation system has to be developed as a whole, and the energy consumption of the controlled and control system have both to be considered. At the present time, there are no readily available modeling methods and analysis algorithms which could be used in the early design phases.

Selected related work is mentioned in the text.

2. Modeling the energy consumption of automation systems

Modeling methods should be developed for discrete automation systems in such a way that the energy consumption beside other parameters can be modeled, estimated, and finally reduced (or optimized in conjunction with other design issues). There are different levels of abstraction on which embedded systems can be evaluated for this task [11]. While there are some methods for the quite exact computation of energy consumption, they all require very detailed knowledge of the system under design. The description has to be on a very low level, which is available only in later phases of the design process.

In this work we concentrate on early design steps, in which major architectural decisions are made, which may have a significant impact on the overall system's energy consumption. Therefore, more abstract models will be necessary because low-level information is not available yet.

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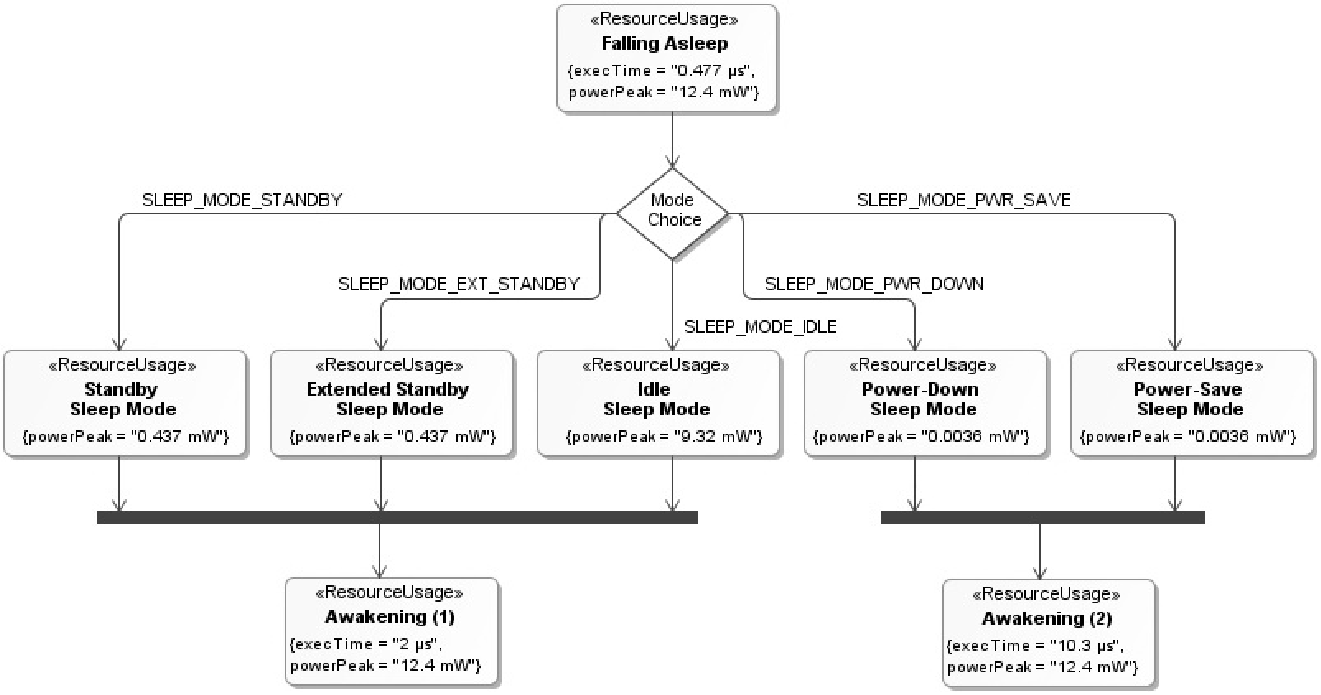

Figure 1. Microcontroller sleep modes

The Unified Modeling Language (UML) is an industry standard for the description of software systems. However, it is not intended to describe system properties equally well as there are no constructs for non-functional properties. Domain profiles of the UML have been developed for this task, namely, the MARTE Profile (Modeling and Analysis of Real-Time and Embedded Systems) [9] as a successor of the UML SPT profile [8]. With its help, non-functional properties like machine utilization, failures, temporal relations etc. can be described. The profile was developed especially for embedded systems and, hence, is suitable for our purposes better than the standard UML alone.

As a research target, a microcontroller development board was chosen because its structure is simple enough for our purposes and it supports different operating modes for power-saving. The ATMEL microcontroller ATxmega128A1 [4] on the development board Xplain [5] was selected for this goal. It belongs to the XMEGA series [3] which supports so-called picoPower technology.

To derive the necessary basic information, the microcontroller board has been tested and measurement experiments have been carried out. Thereafter, a state machine was developed by means of the UML. Descriptions of states are made using the *ResourceUsage* stereotype of the MARTE profile. This package was specially created for the consideration of the resource consumption in the system. For our aim, we take two of the given attributes. These are *execTime* that reflects the duration of staying in each state (in clock cycles or in seconds) and *powerPeak* that represents the necessary power for the state (in Watt). By means of this stereotype, Fig. 1 was created.

It represents all the possible activities of the microcontroller in the non-active mode under the following conditions: utilization of the internal oscillator operating on the frequency of 2 MHz, supply voltage $V_{CC} = 3.3\ V$, ambient air temperature $T = 24°C$.

According to [4], the microcontroller under consideration requires one clock cycle for falling asleep independent of the sleep mode chosen. With an oscillator frequency of 2 MHz, this means approximately $0.477\ \mu s$. The power consumption in this state is approximately the same as in the active mode (measured average value: $12.4\ mW$).

The duration of the sleep mode in this general model is not specified as it depends on the actual application program. Power consumption of the sleep modes varies considerably. It has a significant influence on overall power consumption of the microcontroller. The highest value ($9.32\ mW$ in Idle sleep mode) and the lowest one ($0.0036\ mW$ in Power-save and Power-down sleep modes) differ by several orders of magnitude. The choice of the right sleep mode depends on which parts of the microcontroller need to be active.

Awakening of the microcontroller requires approximately the same power as in active mode. The duration of this process depends on the sleep mode and the type of oscillator in use (external or internal) as well as its frequency. According to [4], sleep modes can be divided into two groups depending on the "sleep depth". Members of these groups are joined by the black bars in the Fig. 1. In each of these groups, all the sleep modes require the same time for awakening. As a result, there are only two states expressing all the possible ways of the microcontroller's awakening under the conditions specified.

It should also be noted that energy consumption can be described in even greater detail by using a MARTE extension termed Dynamic Power Management (DPM) profile, which has been recently developed at Tampere University of Technology [2]. By means of this profile, power aspects of embedded systems can be described. Its main idea consists in creating an individual state machine for each hardware component, which includes the necessary information for calculating energy consumption. However, we do not use this profile for our models in this paper by hypothesis that the ordinary physical formula for the power calculation namely

$$P = I \cdot U$$

gives a relative error in the limit of only 5% relative to the more detailed formula used in the DPM profile.

3. Performance evaluation of energy consumption

For the existing models, simulation and analysis procedures have to be developed or adapted so that alternatives can be evaluated and optimized with the help of heuristic procedures. The technologies developed should be implemented in software tools.

UML models adopting the MARTE profile contain the necessary information for an energy consumption estimation. However, they are not usable directly, as UML models are not semantically well-defined for a specification of the resulting stochastic process. There are two possible alternate routes for this issue: either the models are interpreted or enriched in a way to make them analysable (as it is, for instance, done in [7] outside the area of energy-related issues, or in [6] for energy), or the models are automatically transformed into a model for which analysis algorithms exist. For this work, we propose the second option, and will transform the models into stochastic Petri nets [15], so that the behavior and the properties are preserved. This is an extension of an earlier work, in which extended UML statechart models were transformed into uncolored stochastic Petri nets and analyzed [12,14]. A similar approach is taken in [1], where the work mentioned is applied to the energy consumption evaluation. Perhaps, in the future it will be more efficient to use colored Petri Nets for more complex tasks.

Then, it will be possible to evaluate the created models by means of a software tool, which can analyze stochastic

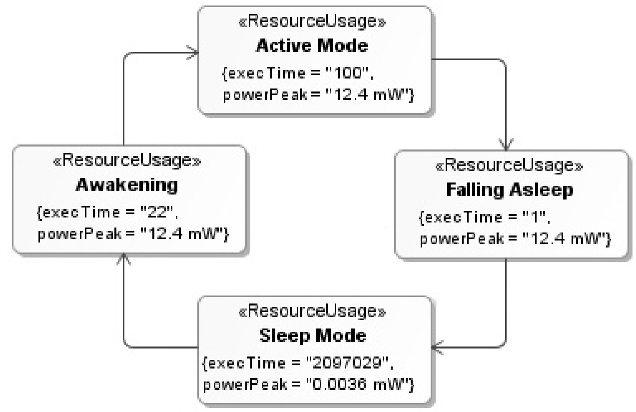

Figure 2. UML model of the microcontroller behavior

Petri nets such as TimeNET [16]. The results will provide information about the energy consumption of a system variation and accordingly a look at the consumption as part of a more comprehensive estimation function. The final tool prototype implementation is envisaged to be a combination of an existing UML tool with a model translation program and an embedded use of TimeNET's analysis modules. It would also be possible to implement a GUI environment for the UML models in the analysis tool, as it has been done for the earlier work mentioned above [13], but this seems to be an unreasonable effort for the more complex models arising from MARTE.

The calculated values of system energy consumption must be validated to prove the correctness of the method in a real example construction.

4. Application example

As a simple example for the field testing, a follow-up program was created. Each second the microcontroller executes 100 operations and – for the rest of the time – stays in the Power-save sleep mode. Figure 2 illustrates this process.

For convenience, execution time is given in clock cycles instead of seconds. For the oscillator operating on the frequency of 2 MHz, one clock cycle is about 0.477 μs. This value was already met in Fig. 1 as the duration of falling asleep. So, this state requires one clock cycle.

In our case, the microcontroller wakes up from the Power-Save sleep mode. As it can be seen in Fig. 1, the respective state *Awakening (2)* requires 10.3 μs or 22 clock cycles. 100 operations will be done in 100 clock cycles. As opposed to the sleep modes where the power values vary considerably, the energy consumption of the microcontroller in the active mode stays constant in close limits. We take the average value of the necessary power (12.4 mW). Our

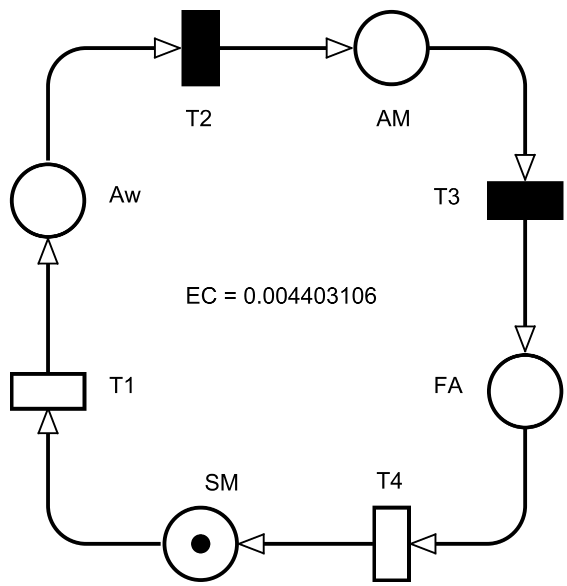

Figure 3. Petri Net indicating the microcontroller behaviour

experiments showed that for different operations, the microcontroller requires from $11.79\ mW$ to $13.02\ mW$. In this case, the maximal relative error of the calculation is only 5%. For the remaining time, 2 097 029 clock cycles, the microcontroller stays in the sleep mode.

The UML model in Fig. 2 is converted to a Petri net (Fig. 3). By its means, it is easy to calculate the power of the microcontroller executing the program. The model was analyzed with the tool TimeNET [16]. The result (in mW) is given in Fig. 3 under the name *EC*. In this case, energy consumption of the microcontroller in one second is determined to be $4.403\ \mu J$.

5. Conclusion

This paper presented a methodology for model-based engineering of energy-efficient automation systems. The UML language extended with the MARTE profile is used for the modeling process. The models are converted into stochastic Petri nets, which are then used for a performance evaluation. An Atmel microcontroller board has been used as an application example, for which the energy consumption has been calculated based on the model.

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